

**A STUDY INTO THE EARTHQUAKE RESISTANCE
OF CIRCULAR ADOBE BUILDINGS**

by

Watcharin Jinwuth

10616833

A thesis submitted in fulfilment of the requirements

For the degree of

Doctor of Philosophy

Faculty of Design Architecture and Building

University Technology of Sydney

CERTIFICATE OF AUTHORSHIP/ ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.



Watcharin Jinwuth

November 2012

ACKNOWLEDGMENTS

The thesis has not been completed without the support and encouragement of a number of people. In particular, I would like to thank;

- My supervisor, Prof. Bijan Samali, who provided the invaluable support, motivation and time throughout the process of the dynamic testing and writing this thesis.
- My ex-supervisor, Dr. Kevan Heathcote, for his tireless contributions to many aspects of this project and his understanding during difficult times, which have been greatly appreciated.
- My co-supervisor, Dr. Cynthia Wang, for her constant advice, proof-reading, critical comments and encouragement throughout the period of my research.
- My mudbrick helper: Peter Hickson, for his guidance, friendship and support.
- The Lapaloma hotel technician: Khemachat Phaensanit and his staff, for their support in relation to tilt table construction and testing.
- The Thai government for financial support for this research project.
- The University of Technology, Sydney (UTS) and the Faculty of Design Architecture and Building staff, especially Ann Hobson for her friendship and support.
- The UTS Engineering structures laboratory staff: Rami Haddad, David Hooper, Dave Dicker, Peter Brown, Ulrike Dackermann and Scott Graham, for their extensive and willing assistance in all aspects of the experimental testing.
- Hamidreza Valipour, for his willing assistance in FEM analysis and experimental testing.
- My family who provided continual support and love during the past four years.
- Ian, a primary proof-reader and his family for their hospitality and assistance during my time in Australia.
- Nuch, Wise and Ward for their enduring love, support and patience.

PUBLICATIONS

The following publications have been generated as part of this research project.

Conference papers

Jinwuth, W., Samali, B., Heathcote, K. & Wang, C. 2010, '*A Study into the earthquake resistance of circular adobe buildings using static tilt tests*', paper presented to the 2010 AEES Conference, Perth, 26-28 November.

Samali, B., Jinwuth, W., Heathcote, K. & Wang, C. 2011, '*Seismic capacity comparison between square and circular plan adobe construction*', paper presented to the Twelfth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-12), Hong Kong, 26-28 January.

TABLE OF CONTENTS

CERTIFICATE OF AUTHORSHIP/ ORIGINALITY.....	0.....	ii
ACKNOWLEDGMENTS.....		iii
PUBLICATIONS.....		iv
TABLE OF CONTENTS.....		v
LIST OF FIGURES.....		xi
LIST OF TABLES.....		xx
ABSTRACT.....		xxiii
Chapter 1 Introduction.....		1
1.1 Background to adobe construction.....		1
1.2 Seismic vulnerability of adobe buildings.....		5
1.2.1 Distribution of adobe buildings in seismic areas.....		7
1.2.2 Historical earthquake damage to conventional adobe buildings.....		8
1.2.3 Factors affecting building damage.....	0.....	11
1.3 Effect of shape on earthquake resistance.....	0.....	12
1.4 Aim of thesis.....		15
1.5 Scope of the study.....		15
1.6 Limitations.....		16
1.7 Research methodology.....	0.....	16
1.8 Thesis layout.....		17
Chapter 2 Previous Researches into the Seismic Resistance of Earth Buildings.....		19
2.1 Introduction.....		19
2.2 Adobe researches of the Catholic University of Peru.....		21
2.3 Static tilt tests of a tall cylindrical liquid storage tank.....		26
2.4 Tilt-table-testing of the FUNDASAL, El Salvador.....		30

2.5	Seismic strengthening of adobe-mud brick houses.....	33
2.6	Getty Seismic Adobe Project, U.S.A.	40
2.7	Shake table testing of scaled geogrid-reinforced adobe models.....	47
2.8	Adobe models testing of the University of Kassel, Germany.....	50
2.9	Adobe guidelines and manuals.....	52
2.9.1	International Association for Earthquake Engineering (IAEE).....	53
2.9.2	The Australia Earth Building Handbook.....	56
2.9.3	Earthquake Tips.....	59
2.9.4	Earthquake-Resistant Construction of Adobe Buildings: A Tutorial.....	61
2.10	Summary.....	64
Chapter 3	Seismic Performance of Adobe Buildings.....	66
3.1	Introduction.....	66
3.2	Earthquake Definition.....	66
3.3	Typical damage patterns and failure mechanisms.....	68
3.4	Static and Dynamic Analysis	74
3.4.1	Static method.....	74
3.4.2	Dynamic method.....	75
3.5	Seismic Design Code for Earth Building Regions.....	77
3.5.1	Concept of seismic code.....	77
3.5.2	The earthquake codes of case studies' regions.....	81
3.6	Summary.....	87
Chapter 4	Performance of Existing Circular Earthen Houses located in Seismic Regions.....	88
4.1	Introduction.....	88
4.2	Hakka earth buildings in China.....	91
4.2.1	Background.....	91

4.2.2	Architectural and structural features.....	92
4.2.3	Building performance in earthquake.....0	99
4.3	Bhunga houses in India.....	100
4.3.1	Background.....	100
4.3.2	Architectural and structure features.....0	104
4.3.3	Building performance in earthquake.....0	104
4.4	Yomata houses in Malawi.....0	106
4.4.1	Background.....	106
4.4.2	Architectural and structural features.....	108
4.4.3	Building performance in earthquakes0	110
4.5	Summary.....0	112
Chapter 5	Simple Static Earthquake Design Method.....0	114
5.1	Introduction.....0	114
5.2	Description of static design method.....0	114
5.3	Relationship between design loads and tilt table performance.....	117
5.3.1	Maximum normal stress for design condition.....(0000)	117
5.3.2	Maximum normal stress for models.....(0000)	119
5.3.3	Hypothesis of the failure criteria as link between design and model behaviours.....0	120
5.4	Theory of reduced model testing.....(0000)	121
5.5	Calculations of static design loads of the existing circular adobe houses.....0	123
5.6	Summary.....0	127
Chapter 6	Brick Fabrication and Material Property Tests.....0	128
6.1	Introduction.....(0)	128
6.2	Brick fabrication.....(0)	128
6.3	Material property testing.....(00000)	132

6.3.1	Specifications.....	132
6.3.2	Testing method.....0	135
6.3.3	Results.....0	137
6.4	Summary.....	139
Chapter 7	Seismic Capacity Comparison between Square and Circular Plan Adobe Construction using Tilt-table Testing.....	140
7.1	Introduction.....	140
7.2	The relationship between the static design load and tilt table testing.....0	141
7.3	Static tilt table	141
7.4	Specimen fabrication and specifications.....	144
7.5	Results of the specimens tested.....	146
7.6	Social aspect of circular building.....	149
7.7	Summary.....	153
Chapter 8	Experimental Procedures of Static Test.....	154
8.1	Introduction.....	154
8.2	The hypothesis of the typical failure mechanism.....	156
8.3	Specimen design and construction.....	157
8.4	Detail of experimental procedures of static test.....	160
8.4.1	Procedures of static tilt-table tests.....0	160
8.4.2	Specimen 1A.....0	162
8.4.3	Specimen 2A.....0	164
8.4.4	Specimen 3A.....0	166
8.4.5	Specimen 2B.....0	168
8.4.6	Specimen 3B.....0	170
8.4.7	Specimen 2C.....0	172
8.4.8	Specimen 3C.....0	174

8.4.9 Specimen 2D.....	0..176
8.4.10 Specimen 3D.....	0..178
8.5 Comparative analysis of results from the static tests	180
8.5.1 Effect of roof load.....	0..181
8.5.2 Effect of wall height-to-thickness ratios.....	0..182
8.5.3 Effect of wall height-to-diameter ratio.....	0..184
8.6 Analysis of crack patterns and failure mechanisms	0..186
8.7 Predicted performance of the tilt tests.....	0..187
8.7.1 Prediction based on maximum normal stress	187
8.7.2 Prediction based on overturning about toe.....	0..189
8.7.3 Discussion of the proposed method.....	192
8.8 Summary.....	194
Chapter 9 Comparison between Predicted Performances of Tilt Table Test Specimens with Performance on Shake Table.....	0..195
9.1 Introduction.....	0..195
9.2 Brick fabrication and material properties tests.....	0..197
9.2.1 Brick fabrication.....	0..197
9.2.2 Material properties tests.....	198
9.3 Adobe specimens construction.....	208
9.4 Static pushover test.....	210
9.4.1 Specimen description and test setup.....	210
9.4.2 Testing procedure.....	212
9.4.3 Experimental result and discussion.....	212
9.5 Shake table testing.....	217
9.5.1 UTS shake table.....	218
9.5.2 Simulated earthquake motions.....	0..219

9.5.3	Scaling of the input time histories.....	220
9.5.4	Predicted results for the dynamic shake tests.....	228
9.5.5	Test setup and instrumentation.....	230
9.5.6	Testing procedure.....	232
9.5.7	Testing and results of specimen 1A.....	234
9.5.8	Testing and results of specimen 3D with openings.....	237
9.6	Summary.....	241
Chapter 10	Application of Design Methodology.....	242
10.1	Introduction.....	242
10.2	Evaluation of an existing building.....	243
10.3	Summary.....	247
Chapter 11	Conclusions and Recommendations for Further Research.....	248
11.1	Conclusions.....	248
11.2	Recommendation for further research.....	250
References	252
Appendices	260

LIST OF FIGURES

Figure 1.1: Taos Pueblo's Mud Villages (built ca. 1000 A.D.)(McHenry 1985).....	2
Figure 1.2: Traditional adobe brick fabrication (Keefe 2005).....	3
Figure 1.3: Construction of a circular adobe house for a homeless project in Thailand.....	4
Figure 1.4: A typical circular adobe house for homeless people in Thailand.....	4
Figure 1.5: Breakdown of earthquake-related fatalities in the 20 th century (Coburn 1993).....	5
Figure 1.6: World maps of earthen architecture (a) and seismic hazard risk areas(b) from www.terracruda.com (De Sensi 2003).....	7
Figure 1.7: Earthquake damage to adobe houses Peru-Aug 16, 2007 (Jean Luis Arce /Reuters).....	9
Figure 1.8: Collapsed Adobe structures by Bam Earthquake Jan 14, 2004 (World Housing Encyclopedia).....	9
Figure 1.9: Losses in the 2001 earthquake in Bhuj, India © Randolph Langenbach, 2007.....	0...11
Figure 1.10: The quake-safe circular Adobe houses in India (swissinfo.ch)	014
Figure 2.1: Seismic Performance of an Unreinforced and a Strengthened Adobe Building in PUCP.....	0.....22
Figure 2.2: Lateral load deformation of static test of unreinforced and reinforced adobe wall's panels in PUCP (Blondet, Garcia & Loaiza 2003).....	00...22
Figure 2.3: Adobe research at PUCP in 1979.....	24
Figure 2.4: Dynamic test of adobe model with cane reinforcement in PUCP.....	25
Figure 2.5: View of the tilt test facilities (Clough & Niwa 1979).....	26
Figure 2.6: Resultant Forces on Inclined Cylinder (Clough & Niwa 1979).....	27
Figure 2.7: The plan of the tilt table (Clough & Niwa 1979).....	28
Figure 2.8: The elevations of the tilt table (Clough & Niwa 1979).....	28

Figure 2.9: Deflected shapes of the model tanks with different base conditions (Clough & Niwa 1979).....	29
Figure 2.10: Basic concept of the static tilt testing (Pena & Lopez 2007).....	30
Figure 2.11: Tilt table with 40 degrees for maximum angle (Pena & Lopez 2007).....	31
Figure 2.12: The collapsed of the front wall of traditional adobe house when tilting reach 14 degree (Pena & Lopez 2007).....	31
Figure 2.13: Commencement of cracking of reinforcement house in the side wall at 30 degrees and cracking in the front and rear walls at 34 degrees (Pena & Lopez 2007).....	31
Figure 2.14: Specimen configuration and dimensions of u-shaped wall unit (Dowling 2006).....	33
Figure 2.15: Vertical corner cracking of unreinforced u-shaped adobe wall testing at UTS, Sydney (Dowling 2006).....	34
Figure 2.16: Preparation of reinforced u-shaped adobe wall unit at UTS (Dowling 2006).....	34
Figure 2.17: Detail reinforcement of model adobe house at UTS (Dowling 2006).....	37
Figure 2.18: Damaged model adobe house retrofitted with string, bamboo, wire and timber ring beam at UTS (Dowling 2006).....	37
Figure 2.19: Model house 4 (a) and model house 7 (b) prior to testing (E. Leroy Tolles 2000).....	41
Figure 2.20: Model house 10 (a) and model house 11 (b) configuration (E. Leroy Tolles 2000).....	42
Figure 2.21: East wall of Model house 4 (a) after test level X and east wall of model house 7 (b) after test level X(2) (E. Leroy Tolles 2000).....	43
Figure 2.22: West wall of Model house 6 (a) after test level VIII and west wall of model house 8 (b) after test level X (E. Leroy Tolles 2000).....	43
Figure 2.23: Out-of-plane failure of Model house 10 (a) after test level VIII and north wall of model house 11 (b) after test level VIII (E. Leroy Tolles 2000).....	43

Figure 2.24: U-shaped adobe wall configuration (Tipler et al. 2010).....	48
Figure 2.25: Tilt testing of the U-shaped adobe wall (Tipler et al. 2010).....	48
Figure 2.26: Tilt testing of the U-shaped adobe wall (Tipler et al. 2010).....	49
Figure 2.27: Simulation of seismic shocks (Minke 2000).....	50
Figure 2.28: Earthquake resistant of earthen buildings in circular shape (left) and square shape (right)(Minke 2001).....	51
Figure 2.29: Field strength test of soil (a) and adobe block (b) (IAEE 1986).....	55
Figure 2.30: Ribbon test (Walker & Standards Australia 2002).....	56
Figure 2.31: Sedimentation test (Walker & Standards Australia 2002).....	56
Figure 2.32: Roll Test (CTAR/COPASA,2002 cited in Blondet, M. & Brzez 2003)....	62
Figure 2.33: Configuration of opening guideline (RESESCO, 1997 from WHE).....	63
Figure 3.1: Types of Fault (NICEE 2002a).....	67
Figure 3.2: Earthquake-induced inertia force of masonry houses (Source: IITK- Earthquake Tips).....	68
Figure 3.3: Definition of In-plane and Out-of-plane walls.(Source: City University, London).....	69
Figure 3.4: In-plane crack pattern.....	70
Figure 3.5: Inclined cracking in the wall in Pinarkaya (Source: GFZ-German Research Centre for Geosciences).....	70
Figure 3.6: Out-of-plane flexural crack pattern.....	71
Figure 3.7: Cracking and separation of walls in 1997 Jabalpur Earthquake (Source: World housing Encyclopedia, reports # 23).....	71
Figure 3.8: In-plane failure pattern.....	72
Figure 3.9: In-plane shear failure – San Giuliano (Marrow) (Source: Conservationtech.com).....	72
Figure 3.10: Various types of failure in adobe structures under seismic excitations (GINELL & Tolles (n.d.)).....	73

Figure 3.11: Seismic zoning map of peak ground acceleration (PGA) of China (RP = 475 years; PE = 10%/50 years) (GB 18306 – 2001 – A1).....	82
Figure 3.12: Seismic effective coefficient curve of GB50011-2001 (IISSE 2002).....	83
Figure 3.13: Seismic zoning map of India (IS 1893:2002) (Source: The Institute of Seismological Research (ISR)).....	84
Figure 3.14: Seismic hazard map of Africa (Source: GSHAP-Global Seismic Hazard Assessment Project).....	86
Figure 4.1: Seismic Hazard map of Asia (Source: Global Seismic Hazard Assessment Program, Switzerland).....	88
Figure 4.2: Seismic Hazard map of the Western Hemisphere (left) and Europe, Africa and the Middle East (right) (Source: Global Seismic Hazard Assessment Program, Switzerland).....	89
Figure 4.3: Seismic intensity zoning map in China.....	91
Figure 4.4: The map shows the location of Hongkeng village.....	93
Figure 4.5: The view of Hongkeng village where the most earth buildings are located.....	95
Figure 4.6: The Zhencheng Buidling was built in 1912 is the biggest circular earthen form at Hongkeng village (Source: www.painaima.com).....	95
Figure 4.7: Ground floor plan of the circular earthen form.....	96
Figure 4.8: The 2nd- 4th floor plans of the circular earthen form.....	96
Figure 4.9: The roof plans of the circular earthen form.....	97
Figure 4.10: The cross section of the circular earthen form.....	97
Figure 4.11: The wooden frame supported the inner earthen wall (Prof. Sunny Cai, 2008).....	98
Figure 4.12: Earthen wall with small openings (Prof. Sunny Cai, 2008).....	98
Figure 4.13: Seismic zoning map of Gujarat (Source: The Institute of Seismological Research (ISR)).....	100
Figure 4.14: Map of district of Kutch of Gujarat State (India).....	101

Figure 4.15: Typical circular earthen hut of Kutch district (Amir January 2005).....	101
Figure 4.16: Plan of the circular typical building.....	102
Figure 4.17: Section of the circular house.....	103
Figure 4.18: Light roof structure of Bhunga house.....	103
Figure 4.19: Bhunga houses in India.....	104
Figure 4.20: Seismic hazard map of Africa.....	107
Figure 4.21: A traditional Yomata with thatched roof.....	108
Figure 4.22: Typical Yomata buildings.....	109
Figure 4.23: The typical plan of Yomata house.....	109
Figure 4.24: The typical roof structure of Yamata house.....	110
Figure 4.25: The typical section of Yamata house.....	110
Figure 5.1: Horizontal design earthquake loads for single story building.....	118
Figure 5.2: Shear forces of circular adobe building.....	118
Figure 5.3: Shear forces on circular adobe model at failure angle.....	119
Figure 5.5: Comparison between the seismic zoning maps produced by China Earthquake Administration (CEA) (right) and that produced by the Global Seismic Hazard Assessment Program (GSHAP) (left).....	124
Figure 5.6: Comparison of the peak ground acceleration for each case study's region rely on the global seismic hazard map.....	124
Figure 6.1: Mixing of mud for adobe bricks.....	130
Figure 6.2: Making adobe bricks by mould.....	130
Figure 6.3: (a)Drying of adobe bricks; (b) Stacked adobe bricks.....	130
Figure 6.4: Sedimentation test.....	131
Figure 6.5: The sequence of construction for adobe compression prisms.....	134
Figure 6.6: Compression machine at NU.....	135
Figure 6.7: Compression test with specimen C1.....	136
Figure 6.8: Types of failure pattern of compression prisms (specimen C3 & C5)....	0.137

Figure 7.1: Conceptual scheme of the static testing.....	141
Figure 7.2: Tilt table configuration and dimensions.....	142
Figure 7.3: Construction of the tilt table.....	143
Figure 7.4: Tilt testing of a square adobe model.....	143
Figure 7.5: Square and circular specimens' configurations and dimensions.....	145
Figure 7.6: Tilting the square specimen and first crack appearing at 20 degrees.....	146
Figure 7.7: The failure modes of the square specimen when tilted further.....	146
Figure 7.8: Tilting the circular specimen and first crack appearing at 29 degrees.....	147
Figure 7.9: The failure modes of the circular specimens when tilted further.....	147
Figure 7.10: The performance of functional areas in circular adobe houses.....	151
Figure 7.11: Circular-adobe-wall construction.....	152
Figure 8.1: Conceptual failure pattern of a circular adobe model in static testing	156
Figure 8.2: Typical specimen configuration.....	157
Figure 8.3: Construction of a circular adobe specimen.....	159
Figure 8.4: The wooden roof cover with bracing.....	160
Figure 8.5: Roof and sand bags installation.....	161
Figure 8.6: Tilting the specimen until cracking and subsequent failure.....	161
Figure 8.7: Reading the result of failure angle.....	161
Figure 8.8: Specimen 1A prior to testing.....	162
Figure 8.9: Testing sequence of specimen 1A.....	163
Figure 8.10: Specimen 2A prior to testing.....	164
Figure 8.11: Testing sequence of specimen 2A.....	165
Figure 8.12: Specimen 3A prior to testing.....	166
Figure 8.13: Testing sequence of specimen 3A.....	167
Figure 8.14: Specimen 2B prior to testing.....	168
Figure 8.15: Testing sequence of specimen 2B.....	169

Figure 8.16: Specimen 3B prior to testing.....	170
Figure 8.17: Testing sequence of specimen 3B.....	171
Figure 8.18: Specimen 2C prior to testing.....	172
Figure 8.19: Testing sequence of specimen 2C.....	173
Figure 8.20: Specimen 3C prior to testing.....	174
Figure 8.21: Testing sequence of specimen 3C.....	175
Figure 8.22: Specimen 2D prior to testing.....	176
Figure 8.23: Testing sequence of specimen 2D.....	177
Figure 8.24: Specimen 3D prior to testing.....	178
Figure 8.25: Testing sequence of specimen 3D.....	179
Figure 8.26: Relationship between roof load and the percentage of horizontal force compare to model own weight.....	181
Figure 8.27: Relationship between wall height-to-thickness ratio and the percentage of horizontal force compare to model own weight.....	183
Figure 8.28: Relationship between wall height-to-diameter ratio and the percentage of horizontal force compare to model own weight.....	184
Figure 8.29: Typical failure mechanisms of circular adobe structures.....	186
Figure 8.30: Failure analysis of the circular adobe specimen.....	189
Figure 8.31: Variation of the first crack angle with the predicted angle.....	192
Figure 9.1: Adobe brick fabrication for the dynamic testing.....	198
Figure 9.2: Sedimentation test of soil composition for dynamic tests.....	199
Figure 9.3: Compressive strength test set up.....	201
Figure 9.4: Typical failure patterns of the compression tests' prisms at UTS.....	202
Figure 9.5: The typical load and time curve from the compression tests (specimen D1).....	202
Figure 9.6: Test setup for the compressive strength test of adobe prisms.....	205
Figure 9.7: Chord modulus of elasticity (MSJC 2005; Rai 2005).....	205

Figure 9.8: The typical stress-strain curve of the adobe prisms (specimen D1).....	206
Figure 9.9: Specimen 1A and 3D (with openings): configuration and dimensions.....	208
Figure 9.10: Three circular adobe models under construction at UTS.....	209
Figure 9.11: Completed three specimens and drying.....	209
Figure 9.12: The pushover test setup of the specimen 1A.....	210
Figure 9.13: The curve push-plate.....	211
Figure 9.14: Instrument locations for the pushover test.....	211
Figure 9.15: Specimen 1A prior to the pushover testing.....	212
Figure 9.16: Failure crack patterns at the southwest side wall.....	213
Figure 9.17: Failure crack patterns at the southeast side wall.....	213
Figure 9.18: Displacement graph of the pushover-testing result.....	214
Figure 9.19: Damages sequence of the specimen from the static pushover testing.....	215
Figure 9.20: UTS shake table.....	218
Figure 9.21: The acceleration time history of 1940 El-Centro earthquake with Peak Ground Acceleration of 0.35g registering 7.1 magnitude.....	220
Figure 9.22: Simulation of the specimen 1A using FEM.....	224
Figure 9.23: Test set up for the impact hammer testing.....	226
Figure 9.24: Impact hammer hit.....	227
Figure 9.25: Modal Analysis of the circular model.....	228
Figure 9.26: Instrumentation locations and direction of motion.....	230
Figure 9.27: LVDT displacement transducer and accelerometer at the north wall (specimen 1A and 3D).....	231
Figure 9.28: Instrumentation locations of the specimen 3D with openings.....	231
Figure 9.29: Specimen 1A and 3D: instrumented and ready for testing.....	233
Figure 9.30: Specimen 1A after simulation S13.....	235
Figure 9.31: Specimen 1A after simulation S14 and its damage at the SE wall.....	235
Figure 9.32: Specimen 3D after simulation S13.....	238

Figure 9.33: Specimen 3D: damage from simulation S14.....	238
Figure 9.34: Failure analysis of the specimen 3D with openings.....	239
Figure 10.1: Failure analysis of the existing circular adobe house.....	243
Figure A-1: The acceleration time history of 1940 El-Centro earthquake with Peak Ground Acceleration of 0.35g.....	262
Figure A-2: The acceleration time history of 1994 Northridge earthquake with Peak Ground Acceleration of 0.88g.....	262
Figure A-3: The acceleration time history of 1995 Kobe earthquake with Peak Ground Acceleration of 0.84g.....	263
Figure A-4: The acceleration time history of 2001 El Salvador earthquake with Peak Ground Acceleration of 0.74g.....	263
Figure A-5: Failure analysis of specimen 3D with openings.....	264
Figure A-6: Failure mode of the Bhunga house.....	266

LIST OF TABLES

Table 1.1: Major earthquakes in regions where adobe buildings are located.....	10
Table 2.1: U-shaped adobe wall units testing at UTS: specifications and results (Dowling 2006).....	35
Table 2.1: (continued) U-shaped adobe wall units testing at UTS: specifications and results (Dowling 2006).....	36
Table 2.2: Simulated seismic motions for GSAP testing.....	42
Table 2.3: Specifications and results of adobe model testing at GSAP (E. Leroy Tolles 2000).....	44
Table 2.3 (continued): Specifications and results of adobe model testing at GSAP (E. Leroy Tolles 2000).....	45
Table 2.4: Earthquake scale factors of the research at University of Auckland.....	48
Table 2.5: Recommendation from IAEE guidelines (1986).....	54
Table 2.6: Recommendations from the Australia Earth Building Handbook (Walker & Standards Australia 2002).....	58
Table 3.1: Selection of method of seismic analysis (Dowrick 1977).....	76
Table 3.2: Design characteristic period of ground motion.....	83
Table 4.1: History of post-earthquakes in Malawi.....	106
Table 4.2: Comparison of the existing adobe houses' configuration.....	112
Table 5.1: Values for specific shape factors.....	116
Table 5.2: Similitude requirements (Moncarz & Krawinkler 1981).....	122
Table 5.3: Comparison parameters of the existing circular adobe buildings.....	126
Table 5.4: Comparison of the horizontal forces of three case studies' buildings.....	126
Table 6.1: Specifications of compression prisms.....	132
Table 6.2: Results from compression tests of adobe prisms.....	137
Table 7.1: Comparison of specifications between square and circular models.....	145

Table 7.2: Results of the square specimen subjected to static tilt testing.....	148
Table 7.3: Results of the circular specimen subjected to static tilt testing.....	148
Table 8.1: Small Scale Adobe Models: specifications.....	155
Table 8.2: Results of the tilt-table testing of the nine circular adobe models.....	180
Table 8.3: The comparative results of varying roof loads.....	181
Table 8.4: The comparative results of wall height-to-thicknesses ratio.....	182
Table 8.5: The comparative results of wall height-to-diameter ratio.....	184
Table 8.6: Results of the static tilt testing based on maximum normal stress.....	187
Table 8.7: Predicted angles using the mean value of the maximum normal stress.....	188
Table 8.8: Results of the prediction based on overturning about toe.....	191
Table 9.1: Adobe prisms specifications for compressive strength testing.....	200
Table 9.2: The results of compressive strength of tested prisms.....	201
Table 9.3: Comparisons of the compressive strength of adobe bricks.....	203
Table 9.4: UTS shake table specifications.....	218
Table 9.5: Earthquake records for the shake testing.....	219
Table 9.6: Comparison of the prototype and small-scale parameters.....	222
Table 9.7: Comparisons of the building period's formulas from a various earthquake codes.....	223
Table 9.8: Values of the fundamental natural of frequencies and scale-differences between prototypes and scale models.....	225
Table 9.9: Specimens 1A and 3D: natural frequencies and damping ratios.....	228
Table 9.10: Testing sequence of the shake table testing for each simulation.....	232
Table 9.11: Classification of damage to buildings (IAEE 1986).....	233
Table 9.12 Specimen 1A: testing sequence and summary of observations.....	234
Table 9.13 Specimen 3D: testing sequence and summary of observations.....	237
Table 10.1: Summarization of the specification of Bhunga house	243
Table 10.2: Ranges of PGA for Modified Mercalli Intensities (Wald et al. 1999).....	245

Table A-1: Results of the compression tests at UTS lab.....	261
---	-----

ABSTRACT

Unreinforced adobe or mud-brick structures have in the past suffered severe damage from seismic forces and have caused a vast number of deaths. However, a number of adobe buildings located in seismic regions have performed well under several seismic events. Most of these traditional buildings are symmetrical in shapes which have significant bearing on the performance of the buildings during strong earthquakes. Most existing circular adobe houses have performed well in withstanding earthquakes even though some did not have any additional ductile reinforcements.

This thesis presents a series of tilt table tests conducted to study the performance of unreinforced circular adobe buildings subjected to earthquake forces. Nine small-scale models (1:3 scale) of adobe structures were built with a variety of configurations and roof loads. The adobe house models were subjected to a constant acceleration when tilted on a tilt-up table. The lateral component of the models weight was used as a parameter to quantify the maximum seismic force for each model. The results then developed a methodology for designing circular adobe buildings to resist earthquakes in specific seismic zones and for specific site conditions.

A static pushover test and two shake table tests were also conducted in order to evaluate the reliability of the predictive model from the tilt table tests. The research outcomes give simple and effective solutions for construction of new adobe buildings located in seismic hazard areas. It can also be applied to evaluate existing circular adobe buildings for their seismic resistance which can assist in predicting the likely outcome in the event of an earthquake.

Keywords: Adobe construction, mud-brick, earthquake resistance, circular building, tilt table test, static pushover test, shake table test.